Echocardiography in shock

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Purpose of review
The aim of this study was to illustrate the varying roles of echocardiography in all phases of shock ranging from a rapid, diagnostic tool at the bedside, to a tool for monitoring the adequacy and effects of shock treatment and finally for identification of patients suitable for de-escalation of therapy.

Recent findings
Echocardiography has become an indispensable tool for establishing diagnosis in patients with shock. It is also important for assessing the adequacy of treatment such as fluid resuscitation, vasopressors and inotropes by providing integrated information on cardiac contractility and systemic flow conditions, particularly when used in conjunction with other methods of advanced haemodynamic monitoring. Apart from a traditional, diagnostic role, it may be used as an advanced, albeit intermittent, monitoring tool. Examples include the assessment of heart-lung interactions in mechanically ventilated patients, fluid responsiveness, vasopressor adequacy, preload dependence in ventilator-induced pulmonary oedema and indications for and monitoring during extracorporeal life support. Emerging studies also illustrate the role of echocardiography in de-escalation of shock treatment.

Summary
This study provides the reader with a structured review on the uses of echocardiography in all phases of shock treatment.

Keywords
cardiac function, echocardiography, haemodynamic monitoring, shock

INTRODUCTION

One-third of the patients admitted to ICUs have circulatory shock [1]. The importance of echocardiography as an aid to management of patients in shock is now established [2–5,6▪▪]. This imaging modality fulfils dual functions: firstly, it may be used as a diagnostic tool to identify the causes of shock and rule out immediately life-threatening and reversible causes; secondly, it is an important tool for titration of therapy and further management.

Important characteristics that make echocardiography particularly useful in the setting of shock are its noninvasive nature and that it can be rapidly applied at the bedside. Nowadays, performing basic critical care echocardiography is a mandatory part of critical care training [7,8]. Most diseases found in shocked patients can be identified using basic level echocardiography. More comprehensive diagnosis such as haemodynamic evaluation and ongoing monitoring is possible but required advanced levels of competency [9].

Thus, echocardiography has a role in all phases of shock, salvage, optimization, stabilization, de-escalation. This review is intended as a pragmatic summary of the application of echocardiography in critically ill patients in these four phases of shock.

ECHOCARDIOGRAPHY IN DIFFERENT PHASES OF SHOCK

Salvage

In the salvage phase, the main role of echocardiography is a focused tool to define the four cardinal types of shock and to obtain a quick working

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KEY POINTS

- Focused echocardiography in the early phases of circulatory shock may be used to rule out important reversible causes of circulatory failure.
- During optimization and stabilization phases of shock management, echocardiography may be combined with other advanced haemodynamic monitoring modalities to detect new diagnoses, to detect deterioration and to avoid harmful effects of therapy.
- In de-escalation of shock treatment, echocardiography and ultrasonography are useful tools for identifying patients in whom inotropic and vasopressor therapy may be safely weaned and fluid may be removed, or for assessing the likelihood of weaning failure from invasive mechanical ventilation.

diagnosis (Table 1, Supplementary videos 1–2, http://links.lww.com/COCC/A45).

Coupled with history, clinical examination and laboratory findings, a focused echocardiographic examination may be used to rule out important reversible causes of circulatory failure (Table 2). Indeed, echocardiography is an integral part of the medical reasoning and arrives *after the clinical examination to answer a question* [10]. In this setting, the focus is on the recognition of different patterns of changes that will support specific diagnoses, and not on time-consuming, detailed measurements. This process is exemplified by asking four key questions, as summarized in Table 2.

A further goal of echocardiography in this phase of shock is to avoid complications and inadvertent injury. Avoidance of intubation in obstructive shock in a patient on the verge of haemodynamic decompensation, avoidance of volume challenges in heart failure and right ventricular dilatation, timely identification of signs of ischaemia to avoid delays to coronary angiography and percutaneous interventions are typical examples. The clinician is reminded that timely identification of shock and its treatment take priority, and lengthy examinations may compromise patient management. For the more experienced echocardiographer, these focused questions may be supplemented by further assessments including Doppler flow profiles. A suggested sequence for the differential diagnosis of shock with the aid of echocardiography and ultrasound for advanced users is included in Supplementary Figure 1, http://links.lww.com/COCC/A44.

Table 1. Classification of shock

Type of shock	Causes
Obstructive	Pericardial tamponade Mediastinal tamponade Chest tamponade, e.g. massive haemothorax, hydrothorax, tension pneumothorax
Cardiogenic	Acute myocardial infarction, acute heart failure, cardiotoxic drugs
Hypovolaemic	Haemorrhagic, gastrointestinal losses, severe dehydration of any cause
Distributive	Sepsis, anaphylaxis, neurogenic
Other, e.g. endocrine	Myxoedema, hypoadrenalism, ketoacidosis

Optimization and stabilization

After the initial resuscitation phase, the clinician is faced with the question of whether there is a resolution of shock or if there is a continued need for haemodynamic optimization.

In the optimization and stabilization phases of shock management, there is a focus on the adequacy of ongoing fluid, vasopressor and inotrope therapy, as well as a consideration of heart-lung interactions in patients on mechanical ventilation. Echocardiography helps to set the haemodynamic goals, which may be successfully achieved and verifies them with a follow-up assessment. Attention should be paid to the analysis of trends and responses to therapeutic interventions. This approach also reduces expenses and associated risks of invasive methods [11].

There is a continued need for monitoring to detect new diagnoses, to detect deterioration and to avoid harmful effects of therapy. Echocardiography is not a stand-alone diagnostic or monitoring tool and is complemented by advanced haemodynamic monitoring techniques such as pulmonary artery catheterization (PAC) or transpulmonary thermodilution (TPTD). Echocardiography provides added information by assessment of cardiac contractile function, intracardiac dimensions and flow profiles. It may be used for the noninvasive estimation of pulmonary artery pressures when the PAC is not available, and the assessment of the adequacy of inotropic therapy by direct measurement of left ventricular systolic function and forward flow. In specific circumstances such as Takotsubo syndrome or stress-induced cardiomyopathies, assessment of Doppler flow profiles will aid the clinician in not only assessing the benefits of inotrope drugs but also potential harms, for example by detecting left ventricular outflow tract obstruction. For mechanically ventilated patients, echocardiography allows the noninvasive assessment of right ventricular function, including pulmonary artery pressures and right ventricular-pulmonary arterial coupling

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Table 2. Important causes of shock to identify on initial focused echocardiographic examination and main findings

Questions	Diagnoses to exclude	Major echocardiographic findings
What is the left ventricular function?	Acute myocardial infarction	Decreased LV systolic function with regional wall motion abnormalities consistent with specific coronary artery territory
	Takotsubo syndrome	Classical apical ballooning, any hypokinesia not consistent with specific coronary artery territory
What is the right ventricular function?	Acute myocardial infarction	RV hypokinesia with or without left ventricular inferior wall hypokinesia
		RV dilatation with tricuspid regurgitation indicating increased pulmonary systolic arterial pressure
	Acute right ventricular dysfunction due to PE	RV dilatation with septal flattening and dyskinesia
	Acute cor pulmonale due to ARDS	
What is the fluid status?	Any hypovolaemia	Small cardiac volumes, intraventricular obliteration ('kissing walls')
		Small inferior vena cava size and total inspiratory collapse in spontaneously breathing patients OR significant decrease in IVC/SVC size in end expiration in mechanically ventilated patients
Is there significant pericardial effusion?	Pericardial tamponade	'Swinging heart', systolic RA compression >1/3 of cardiac cycle or diastolic RV compression or any LV compression.
		'IVC plethora' – fixed, dilated IVC with no/little respiratory variations and hepatic venous flow reversal
Are major valvulopathies present?	Major stenosis, regurgitation or destruction	Any large leakage on colour Doppler, flail leaflet, chordae rupture, valvular destruction

LV, left ventricle; PE, pulmonary embolus; RV, right ventricle.

[12▪,13]. Acute cor pulmonale (ACP) is defined echocardiographically as septal dyskinesia and a dilated right ventricle occurs in about 20% of patients despite lung protective ventilation and is associated with increased mortality [14,15].

Echocardiography may be used to assess fluid responsiveness by evaluating the response to a fluid challenge or passive leg raising. Several methods have been described, including respiratory variations of maximal Doppler velocity in left ventricular outflow tract (ΔVmaxLVOT), velocity time integral measured at the left ventricular outflow tract, superior vena cava diameter (ΔSVC) and inferior vena cava diameter (ΔIVC). In a large observational study of mechanically ventilated patients with circulatory shock of various causes comparing various echocardiographic indices, ΔVmaxLVOT at least 10% had the best sensitivity (79% sensitivity, 64% specificity; AUC 0.752) and ΔSVC at least 21% had the best specificity (sensitivity 61%, specificity 84%; AUC 0.755) for detecting fluid responsiveness in response to a passive leg raising test. Notably, ΔVmaxLVOT at least 10% and ΔSVC at least 21% had similar discriminatory ability and outperformed Δpulse pressure and ΔIVC for predicting fluid responsiveness [16]. The choice of which index to use depends on the availability of a transoesophageal probe, as ΔSVC is only available by this means, as well as whether the clinician prioritizes a 'rule-in' or 'rule-out' test.

Echocardiographic evaluation of cardiac contractility provides further clues for haemodynamic management. A hyperdynamic left ventricle with a small end-systolic left ventricular area, and fast early transmitral filling on pulsed wave Doppler despite fluid resuscitation is indicative of vasoplegia and supports the commencement of vasopressors if not already in place. The diagnosis of vasoplegia is supported by a low diastolic blood pressure or diastolic shock index [17]. Conversely, echocardiography at this stage may demonstrate systolic dysfunction that is not apparent in the very early stages of shock, with vasopressors 'unmasking' hypocontractility when systemic vascular resistance is restored [18]. Ongoing hypoperfusion despite fluid resuscitation and initiation of vasopressors is an indication for repeated echocardiography to assess left ventricular systolic function. Identification of ongoing hypocontractility would be an indication for initiation/titration of inotrope therapy.

Right ventricular failure may occur in patients with preexisting right ventricular dysfunction, volume overload, thromboembolic occlusion of more than 30–50% of pulmonary artery vascular bed or in proximal closures of right coronary artery [6▪▪]. Patients who are mechanically ventilated may have significant heart-lung interactions. An assessment

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of right heart function is useful at this stage to assess the potential deleterious effects of mechanical ventilation on the circulation in patients with ARDS. Among patients subjected to lung protective ventilation, Boissier *et al.* [14] found that the incidence of ACP was around 20%. ACP was defined as dilated right ventricle associated with septal dyskinesia identified on echocardiography and is independently associated with short-term mortality [14,15] (Supplementary Video, http://links.lww.com/COCC/A45). Echocardiography at this stage identifies deleterious haemodynamic patterns that may be modifiable, for example by manipulation of ventilatory settings and prone positioning.

In patients with acute myocardial infarction complicated by shock, the most frequent cause is severe left ventricular dysfunction. In case of haemodynamic instability with severe left ventricular dysfunction, echocardiography allows identification of ventricular septal defect, papillary muscle rupture or dysfunction, cardiac free wall rupture, ventricular aneurysm and right ventricular failure [19]. Repeated echocardiographic examination may detect elevated left ventricular filling pressures, reduced or preserved ejection fraction accompanied with lung congestion and dyspnoea. Diagnosis of myocardial ischaemia and an early indication for coronary angiography and percutaneous intervention is essential for myocardial recovery and can be made with a combination of clinical findings, 12-lead ECG and echocardiography (wall motion abnormalities) within 10 min after admission. Myocardial biochemistry (cardiac troponins) remains confirmatory in subacute myocardial ischaemia and inconclusive transthoracic echocardiogram/ECG.

Valvulopathies may also be assessed at this stage. Although the initial focused examination should have identified major defects that may account for haemodynamic instability, echocardiography may be used for ongoing assessment of acute vs. preexisting changes. Acute lesions may be functional or due to actual valvular disease. For example, an acute dilatation of the left ventricle due to septic cardiomyopathy may cause a functional mitral regurgitation that may be reversible as septic cardiomyopathy resolves. Similarly, an acute dilatation of the right ventricle due to increased right ventricular afterload in ARDS may be amenable to adjustment of ventilator settings. Of note, the clinician should be aware that assessment of valvulopaties in patients who are haemodynamically unstable requires skill and interpretation within the context of the prevailing flow conditions, thus echocardiographic variables normally used to assess severity may not be applicable. A transoesophageal examination during this phase for the careful assessment of valvular disease is also indicated in patients with signs of infection of unknown origin to rule out endocarditis [20]. The assessment of prosthetic valves requires advanced skills in imaging and interpretation. For patients with prosthetic valves, congenital heart disease and for the assessment of surgical need, a multidisciplinary, and highly specialized team is required.

For patients with pericardial effusion, an assessment of the haemodynamic consequences using measurement of intracardiac flows may add decisions regarding drainage. Although an assessment of pericardial effusion is included in the early stages of shock, repeated assessment if required for patients that continue to be haemodynamically unstable. Tamponade physiology is suggested by clinical signs and supplemented with echocardiographic findings of chamber collapse and echocardiographic pulsus paradoxus (Table 3). However, the latter is difficult to evaluate among patients under mandatory positive pressure ventilation, wherein its absence does not exclude haemodynamically important effects. Instead, the clinician may look for IVC plethora and a dyskinetic motion of the interventricular septum accompanied by a relaxation impairment seen on transmitral inflow (with an early to late peak flow ratio < 1) [21]. Although less frequent, the diagnosis of mediastinal tamponade is technically more demanding, sometimes requiring TEE.

Refractory shock should be considered as a potential indication for extracorporeal life support (ECLS). This is relevant to cardiogenic shock either due to left ventricular or right ventricular failure, when acute support with VA-ECMO (Supplementary Figure1, http://links.lww.com/COCC/A44) may act as a bridge to recovery [22,23]. Hypodynamic septic shock with decreasing cardiac index not matching low systemic vascular resistance is an established indication for VA-ECMO [24,25]. Echocardiography is a key to establishing the indication because obstructive or hypovolaemic causes are relative contraindications for ECLS. In septic shock, profound vasoparalysis with preserved cardiac output as an indication for ECLS remains experimental. Hence, the key parameters to consider are systolic ventricular function, filling pressures and cardiac index. Echocardiography is crucial for maintenance and weaning phases of VA-ECMO, including assessments of the need of additional left ventricular unloading in case of a loss of minimal spontaneous stroke volume and cardiac output during therapy [26,27] (Supplementary Video, http://links.lww.com/COCC/A45). An outline of items addressed with the aid of bedside echocardiography and ultrasound may be found in Table 3.

Thus, during the optimization and stabilization phases wherein treatment is less time-critical compared with the salvage phase, the advanced

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Table 3. Extended echocardiographic examination during the optimization and stabilization phases of shock

	Echocardiographic indices used for assessment
Left ventricular systolic function	Global ejection fraction (basic level: eyeballing, advanced level: Simpson's method) Tissue Doppler systolic velocity (s') at the mitral annulus Mitral annular plane systolic excursion (MAPSE) Velocity time integral at the left ventricular outflow tract ($LVOT_{VTI}$) Regional wall motion abnormalities Global longitudinal strain (GLS) Tei index
Right ventricular systolic function and right sided circulations	Right ventricular dimensions Right ventricular wall motion abnormality RV/LV EDA ratio Septal flattening and dyskinesia Fractional area contraction Tricuspid annular plane systolic excursion (TAPSE) Right ventricular free wall strain Systolic pulmonary arterial pressure estimation using the tricuspid regurgitant (TR) method Mean pulmonary arterial pressure estimation using the pulmonary regurgitant method Pulmonary acceleration time incl. mid systolic notch for identification of pulmonary hypertension Bubble test for patent foramen ovale Contrast examination for extracardiac shunts
Left ventricular diastolic function	E/A ratio E/Ō TR velocity Left atrial end-systolic volume
Fluid Responsiveness	Respiratory variations in response to PLR or fluid challenge in the following: maximal Doppler velocity in left ventricular outflow tract (ΔVmaxAo) velocity time integral measured at the left ventricular outflow tract superior vena cava diameter (ΔSVC) inferior vena cava diameter (ΔIVC)
Pericardial fluid and haemodynamic consequences (tamponade physiology)	Size of effusion (not indicative of pressure) Location of effusion Right atrial systolic collapse >One-third of cardiac cycle Right ventricular diastolic collapse Left atrial collapse Left ventricular diastolic collapse 'Swinging heart' Paradoxical septal movement Echocardiographic 'pulsus paradoxus', i.e. >40% increase in right sided (transtricuspid/pulmonary) concomitantly with >25% decrease in left-sided (transmitral/aortic) flows in inspiration during *spontaneous breathing* (may be absent during mandatory positive pressure ventilation) IVC plethora (fixed, dilated IVC; diastolic flow reversal in hepatic veins)
Valvulopathies	Acute and functional valvulopathies Papillary muscle rupture Mitral valve prolapse Vegetations Valvular perforation
LVOT obstruction	Turbulent flow on colour Doppler in LVOT Pressure gradient in the LVOT>30 mmHg by continuous wave Doppler Dagger shaped LVOT flow on pulsed wave Doppler Systolic anterior motion of anterolateral mitral valve leaflet, mitral regurgitation
Decision on ECLS in a refractory shock	Critically low cardiac index in patients in cardiogenic shock or cardiac arrest Cardiac index insufficient to match critical vasoparalysis in patients with septic shock Assessment of vessels prior to cannulation – catheter sizes Placement of the drainage cannula tip in the right atrium for VA-ECMO, at the Eustachian valve level for the VA-V or VV-ECMO Exclusion of recirculation in the right atrium for the VA-V or VV ECMO Prograde cannulation of femoral superficial artery to secure distal leg perfusion under ultrasound control Spontaneous LV echo contrast in poorly opening aortic valve and decision on additional unloading device (Impella or surgical LV vent) Weaning of VA-ECMO flow under echocardiography control (preload, contractility, stroke volume, ECMO afterload effect) Exclusion of vessel thrombi post ECMO extraction, decision on continuing anticoagulation therapy

ECMO, extracorporeal membrane oxygenation; IVC, inferior vena cava; LV, left ventricle; LVOT, left ventricular outflow tract; VA, veno-arterial; VV, veno-venous.

echocardiographer may choose to expand the repertoire of measurements beyond a focused examination.

De-escalation

The de-escalation phase of shock is usually characterized by stabilized macrosystemic circulation and fluid accumulation. Together with clinical signs and symptoms and other haemodynamic monitoring variables, echocardiography and ultrasonography are useful tools for identifying patients in whom inotropic and vasopressor therapy may be safely weaned and fluid may be removed. The absence

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of fluid responsiveness, increased filling pressures and increased cardiac volumes, in combination with the presence of pathological B-lines on lung ultrasound and a venous congestion, as indicated by a high VeXUS score [28▪], is an indication for fluid de-resuscitation [29▪]. Echocardiography at this stage may also detect persisting or new right ventricular dysfunction that may cause venous congestion and contribute to organ failure.

For patients who are difficult to wean from mechanical ventilation, echocardiography may be helpful for the assessment of weaning-induced pulmonary oedema (WIPO) [30]. Indeed, WIPO occurs in 44–87% of attempt of weaning from mechanical ventilation [31]. Among patients who fail a spontaneous breathing trial, echocardiography may be helpful for detecting WIPO by demonstrating increased left ventricular filling pressures. Further, echocardiography may be useful for detecting silent diastolic and systolic dysfunction that may determine weaning outcome. Particularly in high-risk patients, echocardiography may be used to confirm preload dependence before a spontaneous breathing trial, to improve chances of extubation success [30,31]. Thus, echocardiography-driven investigation may be useful for planning management, for example with diuretics or nitrates, and to rule out ischaemia.

CONCLUSION

Echocardiography may be used in all stages of shock from early diagnosis to continued monitoring and vigilance during optimization and stabilization phases, to de-escalation. In the early stages, a focused examination assists the clinician to define the type of shock and establish a working diagnosis. Later examinations help identify new disease, assess the adequacy of ongoing treatment and may assist in establishing indications for treatment escalation. Echocardiography is an indispensable tool for monitoring during ECLS.

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Conflicts of interest

There are no conflicts of interest.

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- ▪ of special interest
- ▪▪ of outstanding interest

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